

RECENT PROGRESS IN MAGNETO-OPTICS.¹

IT is my intention this evening to give you a general review of the experimental researches which have occupied me during the last few years. They all refer to the relation between magnetism and light, a relation the first and fundamental example of which was discovered in this very institution by Faraday in 1845.

Surely every physicist should feel inspired by the idea of having the privilege to address an audience in the same lecture room, where so often some of nature's deeper mysteries were revealed; and I feel the uplifting force of this inspiration all the stronger, as my own work for many years has been so closely connected with one of Faraday's discoveries. Faraday discovered that the plane in which the vibrations of light take place *rotates* whenever a ray of light is propagated parallel to the magnetic lines of force through some substances, such as Faraday's own heavy glass; this fact we now indicate by the term the magnetic rotation of the plane of polarisation. The discovery of this fact opened the chapter of magneto-optics.

Faraday's mind again and again returned to the relation between magnetism and light, and incessantly he sought for closer and more intimate connections; in one experiment in March, 1862 (which is said to have been his last), he tried to observe a change in the spectrum of a flame when acted on by a magnet. The entry in Faraday's notebook, preserved in this institution with pious care, concludes with the words, "not the slightest effect on the polarised or unpolarised ray was observed." As we now know, the means of Faraday's time were not powerful enough to observe the effect sought for. Various physicists since Faraday have sought in the same direction; some have recorded their negative results, others have not, for most physicists have an almost invincible dislike for the publication of negative results, though a collection of such unsuccessful attempts, if precisely stated, would be most interesting, and should afterwards prove very valuable.

Magnetisation of the Spectral Lines.

In my own case, the thought to submit a source of light to the influence of magnetism occurred to me during a quantitative investigation of the effect discovered by Kerr concerning the light reflected by magnetised mirrors. I was working at the time in Leyden, in Prof. Onnes's laboratory. The account of Faraday's negative experiment encouraged me in my endeavours, and also an argument in 1856 by Lord Kelvin, referred to by Maxwell as the "exceedingly important remark of Sir W. Thomson." If it might be accepted that the forces operating during the propagation of light in magnetised substances exist also whenever the source of light is in the magnetic field, we can expect some direct effect of magnetism on radiation.

My own successful experiments date from 1896 to 1897, whereas three years earlier I also had recorded a negative result, not having then used adequate means.

As you know, a sodium flame chiefly emits two kinds of yellow light, and accordingly its spectrum, when analysed with one of Rowland's large concave gratings, shows two yellow lines. With a grating of medium size these lines have a distance of one millimetre; they are rather narrow as shown in the slide. In August, 1896, I found that when a sodium flame is placed between the poles of an electromagnet, and is looked at with a spectro-scope in a direction at right angles to the lines of force, the yellow lines in its spectrum become somewhat wider when the magnetic field is put on.² This fact can be expressed in a different way by saying that, besides the original vibrations, a flame in a magnetic field emits other vibrations, of which some have a somewhat greater, and some a somewhat smaller, frequency than the original vibrations.

This observation of a small change in a spectral line was the origin of my subsequent work. I realised that this change, however small, was worth a closer examination. Indeed, it seemed clear at once that here we had

a means of studying the internal vibrations of a molecule by modifying in a simple way the conditions under which they are going on. Of course, the result was verified in all directions. As there is now, I think, no doubt as to the reality of the observed changes, I shall only refer very briefly to this stage of the work. In the first place, the widening of the lines was observed in the direction of the lines of force also. Then the fact was established that to the observed *direct* effect there corresponds an *inverse* one. When white light traverses the incandescent sodium vapour we observe the absorption lines; these also are widened when the vapour is subjected to magnetic forces. Secondary influences were discarded by suitable modifications of the experiments. In one case no change was observed. The spectra of fluted bands, such as those of iodine, carbon, or nitrogen, did not show any effect, nor could Becquerel and Deslandres using increased power discover it.

Before I could answer the different questions which presented themselves, I had the advantage that the beautiful theory of the electromagnetic and optical phenomena, developed by my friend Prof. Lorentz, gave its quickening influence to my experimental work.

In this theory it is supposed that the material world is built up of three things: ponderable matter, ether, and electrons. I think it is rather superfluous to remind you here, in the land of Maxwell, Kelvin, Crookes, J. J. Thomson, Schuster, Larmor, Heaviside, and Johnstone

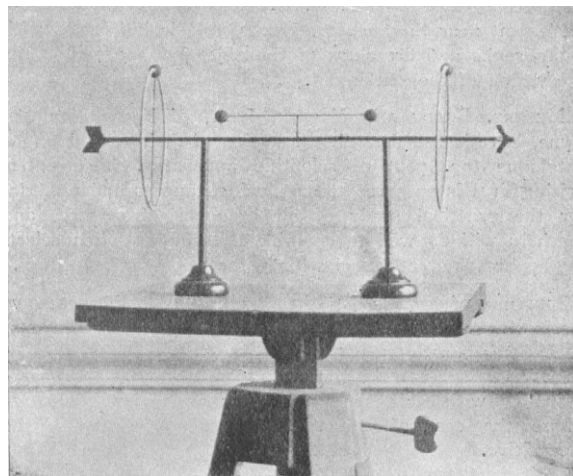


FIG. 1.

Stoney, that electrons or corpuscles are exceedingly small, electrically charged particles, which are supposed to be present in all material bodies.

These electrons can perform oscillations under the influence of the forces which attract them to their position of equilibrium. Because they are electrified they have sufficient hold on the ether to excite in it the electromagnetic vibrations which, according to Maxwell's theory, constitute light. The oscillatory periods of the electrons determine the position of the lines in the spectrum, and with every change in the period of oscillation we observe a displacement of the corresponding line.

In Lorentz's theory the explanation of the effect of a magnetic field is as simple as it is beautiful.

The forces operating on the vibrating electron in a magnetic field are fairly well known. These forces are the same which curve the path of the cathode rays in a vacuum tube which is acted on by a magnet. All motions of the electrons in the molecules of a flame may be supposed to be made up of three particular motions, chosen in such a manner that the action of the magnetic field on each of them can be easily foreseen. The light of the flame is exactly the same as it would be if the flame contained three groups of electrons vibrating in these simple ways. In this model the electrons are represented by red balls; the black arrow indicates the direction of the magnetic force (Fig. 1).

¹ Di-course delivered at the Royal Institution on Friday, March 30, by Prof. P. Zeeman.

² Zeeman, Verslagen Kon. Akademie v. Wetenschappen, Amsterdam, October and November, 1896. *Phil. Mag.*, March, 1897.

As a first simple motion we choose a vibration parallel to the lines of force. On the group of electrons which possess this motion the magnetic force has no influence; the period, which we call T , remains unmodified. The other two simple motions are circular motions, clockwise or anti-clockwise, in planes perpendicular to the lines of force.

An electron performing either of these rotations will be acted on by a force which is directed towards or from the centre, dependent on the direction of the rotation. The magnetic field must, therefore, cause the speed of the electron either to increase or to decrease, and so will either diminish or increase the period. Therefore, instead of one motion with period T , we get under the influence of the field three motions with periods T , $T+v$, $T-v$, v being a small quantity. To each motion of the electrons there corresponds a luminous vibration, according to the electromagnetic theory of light. Observing with a spectroscope we must, therefore, see each spectral line divided into three lines; each line becomes a *triplet*.¹

I will show you a few examples of lines which are really divided into three components, in accordance with Lorentz's theory (Fig. 2, iron; Fig. 3, part of iron spectrum).² You will notice that each of the components remains very narrow; it is not a hazy effect, but a very definite one. This certainly would not be the case if all molecules did

not behave in the same manner, and if certain conditions of isotropy of the molecules were not fulfilled.³

The consideration of the model may illustrate some other points which were foreseen by Lorentz's theory. Consider the light emitted at a right angle to the lines of force. The three kinds of light seen in this direction are each due to vibrations of one kind, and therefore polarised. We can, therefore, extinguish the light of the central component, or of the two external components, of the triplet by a Nicol. In one half of the slide shown the external components are extinguished; in the other half the central one. So, for the first time, we were now able to get polarised radiations from the molecules of a gas. All attempts to produce such simple vibrations from gaseous molecules had hitherto failed.

With some lines the central component and the outer ones differ much in intensity. If this be the case the spectroscope can be dispensed with entirely, and we may observe a partial polarisation of the

light emitted by the vapour in the field as found by Egoroff and Georgiewsky. We shall now consider the light emitted in the direction of the lines of force (Fig. 4).

It is seen at once that each line must split up into two components. Moreover, both lines must be circularly polarised, but in opposite directions. With suitable arrangements, in one half of the field of view the one, in the other the second, component can now be extinguished. I observed this circular polarisation for the first time in the case of the sodium lines now shown. You see how complete the circular polarisation is. There is no trace of rectilinear or of elliptic polarisation.⁴

When I first looked for this circular polarisation, I did not have the field of view divided into two parts, but the position of the line was determined by means of a spider's

¹ Zeeman, *Verslagen Kon. Akademie v. Wetenschappen*, Amsterdam Mei, Juni, October, 1897. *Phil. Mag.*, July and September, 1897.

² The photographs illustrating this lecture are, excepting the diagrams, enlarged copies from negatives. The scale is different in the various cases. The separation of the outer components is of the order of one-sixth of the distance of the sodium lines (the vertical lines in Fig. 5). No. 2 is a copy of one of the first photographs I obtained. The author is indebted to Prof. Runge for No. 11. The photograph is not distinctly shown in the latter reproduction. In the Proceedings of the Royal Institution some additional Figs. will be reproduced.

³ Lorentz, *Annalen der Physik*, Bd. 63, p. 278, 1897.

⁴ Cf. Larmor, "Aether and Matter," p. 345, 1900.

thread. On the reversal of the magnetising current the luminous line moved. I do not wish to disguise the fact that no observation has ever afforded me so much pleasure as this one.

It has already been remarked that we can also study the absorption lines which become visible when white

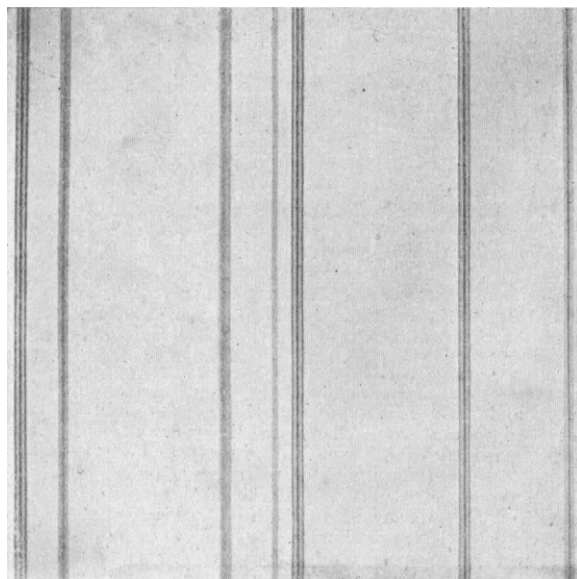


FIG. 2.

light is transmitted through the vapour. We then study the inverse effect. I shall use it to show you at least something directly depending upon the effect, because the effect itself is too young to appear before so large an audience. The inverse effect for light parallel to the lines of force plays a part in an experiment due to Righi.¹ Consider a horizontal ray parallel to the axis of an electromagnet with pierced poles, and let crossed Nicols be placed

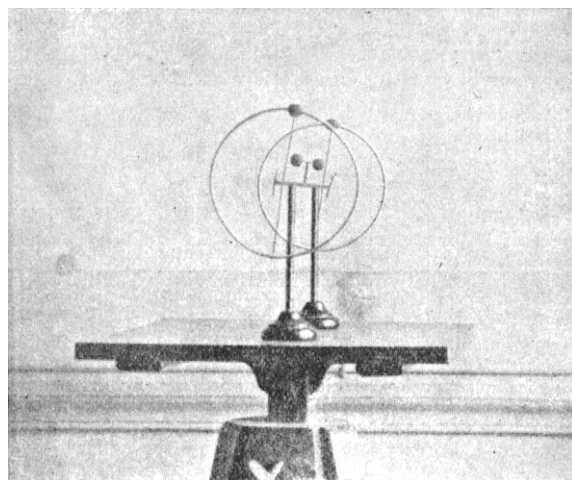


FIG. 4.

before and behind the instrument, as in Faraday's experiment. A sodium flame in the field emitting two kinds of circularly polarised rays absorbs these same radiations, but does not stop the radiations polarised in the opposite

¹ Righi, *C.R.*, cxxvii., p. 216, 1898. *C.R.*, cxxviii., p. 45, 1899. *Nuovo Cim.* (9), 8, p. 102, 1898.

direction. These remaining circularly polarised rays cannot be extinguished by a Nicol.

The brilliant yellow spot which appears on the screen as soon as the current is put on is due to such rays. The explanation of this experiment is not complete, however, at least not for denser vapours. The Faraday rotation of the plane of polarisation then plays a part, as we shall see further on.

The magnetisation of the spectral lines allows us to determine whether positive or negative electrons are vibrating in a flame. From the phenomena in the direction of the lines of force, it follows that in a luminous gas the negative electrons give rise to all vibrations. It does not follow, however, that the luminous molecules have a negative charge. On the contrary, the researches of Lenard and Stark show that at least part of the luminous spectra is emitted by positively charged atoms.

When a line is split up into a triplet, we can, by measuring the amount of the effect, find out how much matter is loaded with the revolving electron, or, in other words, we can determine the ratio of the charge e to the mass m of the electron. In this manner I have made the first determination of this notable number e/m , and found it of the order of magnitude of 10^7 electromagnetic units per gram.¹ The most accurate measurements of the present time for different spectral lines yield values ranging between 1.4 and 1.8 by 10^7 . This number is about 1500 times the corresponding number for hydrogen as deduced from the phenomena of electrolysis.

We must, then, conclude that at least a majority of spectral lines is due to the vibrations of the negative electron. This conclusion is not only valid for incandescent sodium or mercury. All elements which can give colour to a flame or which can be evaporated in a spark show the magnetisation of the spectral lines, and hence in all elements these negative electrons are present.

Independent experimental evidence for the existence of electrons has been derived from the study of the cathode rays in a vacuum tube. The discontinuous structure of electricity was also proved by other phenomena, and in this way physicists were led by purely experimental methods to the negatively charged corpuscle of J. J. Thomson, 1500 times smaller than the hydrogen atom, in full accordance with the electron necessitated for the explanation of the magnetisation of the spectral lines.

All fundamental characteristics of the magnetic resolution of the spectral lines were then explained, and the truth of the explanation proved beyond the possibility of doubt. More detailed knowledge of the effect has been greatly extended by a whole series of investigators, especially by Becquerel, Cornu, Cotton, Michelson, Kent, König, Righi, Reese, Runge and Paschen, and in this country by Gray, Preston, Lodge, Lord Blythwood, and others, and from the theoretical side by Larmor, Fitzgerald, Jeans, and J. J. Thomson.

Not all spectral lines are tripled; some are split up into quartets, others into sextets. The lines D_1 and D_2 in strong fields are an example. The whole of such a system of lines is, even in the strongest fields, confined to the space of one-sixth of the distance of the sodium lines. In some cases still more complicated subdivisions have been observed, especially by Michelson. In such cases the simple electromagnetic model of a molecule emitting light is insufficient. We shall return to this subject afterwards, and first proceed to a discussion of *phenomena accompanying the inverse effect*.

This investigation, which I carried out in Amsterdam together with my pupils, Drs. Hallo and Geest, was suggested by a theoretical investigation by Prof. Voigt, of Göttingen. Lorentz's theory relates to one single vibrating particle, and can only be applied to substances of very small density which emit very narrow spectral lines. With greater density, and therefore broader spectral lines, the mutual influence of the molecules must be taken into account. It seems, however, that a theory of emission of a system of reciprocally reacting molecules is rather difficult. In the case of absorption the problem is easier, and is considered by Prof. Voigt in his theory of magneto-

optical phenomena.¹ He does not deal with the electrons directly, but adds suitable new terms to the equations of motion in an absorbing medium. His method establishes a connection between the rotation of the plane of polarisation and the resolution of the spectral lines, a connection almost simultaneously pointed out by Fitzgerald. This also led to an interesting result, until then missed by the electronic theory, namely, rotation of the plane of polarisation close to an absorption band.

(To be continued.)

MINERAL RESOURCES OF THE UNITED STATES.

FROM time to time we have directed attention to the variety and magnitude of the work being carried on by the United States Geological Survey. Of all the work undertaken, none is of greater value to the general public than that of the division of mining and mineral statistics under the able direction of Dr. David T. Day, whose masterly report (Washington, 1905) on the mineral resources of the United States for 1904 has recently been issued. The volume covers 1264 closely printed pages, and in arrangement and scope is similar to the twenty preceding annual reports of the series. Each chapter is a census of the productive features of the industry under discussion from the pens of statistical experts. The figures dealt with are stupendous. In 1904, for the fifth time, the total value of the mineral production of the United States exceeded the sum of 200,000,000., and it is curious to note that the value of non-metallic minerals exceeded that of metallic minerals by 41,000,000. Iron ore and coal are the most important of the mineral products. Statistics of the production of moulding sand were collected for the first time in 1904. Another novelty is a report, written by Mr. H. H. Hindshaw, directing attention to the occurrence of peat in the United States and to its possibilities as a source of fuel. Appended to the report is a useful bibliography of the subject. Tin ore was produced commercially, though in small quantities, in South Carolina, South Dakota, and Alaska.

There is a constant increase in the demand for such abrasives as corundum and emery, and consequently the publication of Bulletin No. 269 (Washington, 1906), on corundum and its occurrence and distribution in the United States, by Mr. J. H. Pratt, is a welcome addition to technical literature. It is an enlarged edition of Bulletin No. 180, published in 1901, and has grown from 98 pages to 175 pages. It is admirably illustrated with eighteen plates, and constitutes a complete monograph on the three varieties, sapphire or gem corundum, corundum, and emery. All the occurrences in the United States are described, and particulars are added regarding the distribution of corundum in other countries, the methods of mining and cleaning, and the uses of corundum. In conclusion, some useful suggestions to prospectors for chromium are given.

The most remarkable outcome of the recent work of the mining division is the extensive series of tests of the various coals found in the United States. These are recorded in three bulky quarto volumes forming Professional Paper No. 48 (Washington, 1906), and covering 1492 pages. The work was carried out at the coal-testing plant of the United States Geological Survey at the St. Louis Exhibition under the direction of a committee consisting of Messrs. Edward W. Parker, Joseph A. Holmes, and Marius R. Campbell. The first volume describes the field work, classification of coals, and chemical work; the second deals with boiler tests; and the third with producer-gas, coking, briquetting, and washing tests. The results are of far-reaching importance in the solution of the fuel and power problems upon which the varied industries of the United States depend. Most of the American bituminous coals and lignites can, it was found, be used as a source of power in a gas-producing plant, the power efficiency of bituminous coals when thus used being two and a half times greater than

¹ Zeeman, Verslagen Kon. Akademie, Amsterdam, November, 1896, § 23.

¹ Voigt, *Annalen der Physik*, Bd. 67, S. 345, 1899.